NATURAL AND MAN-MADE CLIMATE CHANGES IN THE HOLOCENE

Rustam Gakaev[1], Arun Daukaev[2]
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[1]Kadyrov Chechen State University, RUSSIA
[2]Kh . Ibragimov Complex Institute of the RAS, RUSSIA
rustam.geofak@yandex.ru

Abstract

The article provides a comprehensive analysis of both natural and anthropogenic climate variations over the Holocene epoch, spanning the last 11,700 years. It begins by exploring the natural drivers of climate change, including Milankovitch cycles, which influence Earth's orbital parameters and contribute to long-term climatic shifts, volcanic eruptions that inject aerosols into the atmosphere, and changes in solar irradiance. These factors played a critical role in shaping early Holocene climate patterns, leading to periods of warming and cooling, such as the Medieval Warm Period and the Little Ice Age. As the article progresses, it shifts focus to the growing impact of human activities, particularly from the advent of agriculture and urbanization to the present-day industrial era. The study discusses how early human practices like deforestation, large-scale farming, and the domestication of animals gradually began to influence local and regional climates. However, it is in the post-industrial era that human influence on the climate has dramatically accelerated, primarily due to the combustion of fossil fuels, mass deforestation, and the significant rise in greenhouse gas emissions. This shift marks a transition from predominantly natural climate drivers to an era increasingly dominated by human-induced climate forcing.

Keywords: Holocene, natural climate variability, anthropogenic climate change, volcanic activity, solar insolation, greenhouse gas emissions, deforestation, industrial

I. Introduction

Climate changes have taken place throughout nearly all geological eras and are documented through paleontological discoveries, shifts in archaeological cultures, and other forms of evidence. However, the use of archaeological data for stratigraphic analysis and other studies is limited to the Quaternary period, as it was during this time that a key event occurred: the emergence of humans. Consequently, this period is also known as the Anthropogenic. Fossil remains and artifacts from human material culture serve as the primary paleontological markers for the subdivisions of the Quaternary period. The archaeological method, alongside paleontological research, is applied in various disciplines, including climatology. The Anthropogenic (Quaternary) period is divided into the Pleistocene and Holocene epochs. The Pleistocene is further subdivided into a series of glacial and interglacial stages, including the Günz, Mindel, Riss, and Wurm glaciations, and the Günz-Mindel, Mindel-Riss, and Riss-Wurm interglacial stages.

The Holocene epoch, the focus of this article, represents the second and current epoch of the Quaternary period. In July 2018, the International Union of Geological Sciences (IUGS) officially divided the Holocene into three distinct ages, each marked by climatic shifts: the Greenlandian (11,700 to 8,200 years ago), the Northgrippian (8,200 to 4,200 years ago), and the Meghalayan (from 4,200 years ago to the present), as classified by the International Commission on Stratigraphy. The Greenlandian is characterized by warming after the last ice age. The

Northgrippian is notable for a significant cooling event triggered by the disruption of ocean circulation due to glacial melt. The current age, the Meghalayan, began with a severe drought lasting around 200 years [Fagan, 2021].

The Holocene epoch began around 11,700 years ago, following the Pleistocene, and is the shortest geological epoch, except for the debated Anthropocene, which some scholars argue started in the 1950s. This epoch is marked by significant global warming, the extinction of Pleistocene megafauna, and the broader Holocene extinction, as well as the spread and social evolution of Homo sapiens.

Due to its distinctive climatic characteristics, the Holocene is generally considered an interglacial epoch, showing many similarities to previous interglacial periods. The primary trend in Holocene climate change was the shift from the cold conditions of the late Pleistocene to a warmer climate, with the peak of warming occurring approximately 6,000 years ago. Although the overall climate during the Holocene was relatively stable, researchers have noted considerable variability.

Roughly 14,000 years ago, the Earth's temperature began to rise, initiating the melting of glaciers and the breakup of ice sheets. This warming was global in scope and led to the degradation of the Wurm ice sheets in Europe and the Wisconsin ice sheets in North America. During this process, there were notable fluctuations in temperature, periodic glacier advances, changes in sea levels, the altitude of snow lines in mountain regions, and the extent of valley glaciers and vegetation zones. The Scandinavian ice sheet disappeared about 9,000 years ago, while the North American ice sheet followed around 7,000 years ago.

II. Methods

Based on paleobotanical data, the Holocene is divided into the following climatic periods: Arctic and Subarctic (end of glaciations and beginning of the postglacial period); Boreal (9,000–7,000 years ago) — cool and dry; Atlantic — warm and humid; Subboreal — warm and dry (xerothermic); and Subatlantic — cool and humid [Holocene climate..].

In the Arctic and Subarctic period (11,000–10,000 years ago), warming not only led to the retreat of ice sheets in North America and Europe, but also to the significant reduction of tundra in Europe. Birch-pine and taiga forests began to expand once again.

During the Boreal period, taiga forests continued to spread northward, replacing the tundra, while broad-leaved forests began to dominate southern and central Europe. The melting of glaciers contributed to a rise in sea levels. This period coincided with the Mesolithic (Middle Stone Age), characterized by the increasing settlement of permanent locations, marking a shift toward a more sedentary lifestyle. People still relied on hunting and gathering, although agriculture began to emerge in some regions, and the clan community was the basic social unit.

Around 6,000 years ago, the Holocene climatic optimum began, which is associated with the Atlantic period. According to the Blytt-Cernander classification, the Atlantic was the warmest and wettest phase of the Holocene in Northern Europe. During this time, temperatures were generally higher than today, and half of Iceland was covered in birch forests, compared to just 1% today. The vegetation in Europe was more diverse and included more heat-loving species. The temperate forest zone extended about 5° further north than its current location, and the average annual temperature in Europe was 1-2°C higher than today. In tropical regions, the climatic optimum brought increased humidity and a slight rise in temperature. The Sahara was a savanna, and Lake Chad's water level was 40 meters higher than its current level (11 m). Evidence from different regions in both hemispheres indicates that the Holocene optimum was marked by a warm, humid climate on a global scale.

The Subboreal period (5,000–2,500 years ago) was characterized by cooling, which caused a southward shift of landscape zones toward the equator. This period saw the advance of mountain glaciers in Alaska, Spitsbergen, Iceland, and the Alps, as well as increased ice cover in higher latitudes and greater aridity in already dry regions.

The Subatlantic period, which began about 2,500 years ago (500 BCE) and continues to the present day, brought cooler and wetter conditions. During this time, the climate deteriorated, becoming cooler with increased precipitation, particularly in parts of Europe where precipitation rose by 1.5 times. Peat bogs began to form, and the tundra expanded into forest areas, while forests encroached upon the steppe. Gradually, the climate shifted toward modern conditions, characterized by higher oceanicity. In the early centuries CE, temperature and humidity were similar to today's levels, but by the 4th–5th centuries CE, the climate became dry and warm until the 8th century, during which time peatlands contracted, and lake levels dropped.

III. Results

Khotinsky N.A. and Savina S.S. conducted a detailed analysis of the ancient climate of the former USSR during the Holocene period [1985]. Earlier, N.A. Khotinsky, using paleobotanical research and radiocarbon dating data, identified three major warm phases of the Holocene within the USSR: the Boreal phase (8,300–8,900 years ago or the 7th millennium BCE), the Late Atlantic phase (the climatic optimum, 4,700–6,000 years ago or the 3rd millennium BCE), and the Mid-Subboreal phase (3,200–4,200 years ago or the 2nd millennium BCE). He also determined that the Boreal warming was most prominent in the Northeast and Far East of the USSR, the Late Atlantic phase was widespread across most of Eurasia, and the Mid-Subboreal phase was particularly significant on the northern Russian Plain.

Several researchers, based on paleoclimatic studies, observed that the warm, humid climate of the 4th millennium BCE transitioned into a hot and dry (arid) climate during the 3rd millennium BCE [Idrisov, 2010]. By the middle of the 3rd millennium BCE, the sedentary Kura-Araxes agricultural society was replaced by a population with a radically different economic system [Kornienko, 2013]. Numerous scholars have similarly linked shifts in archaeological cultures to corresponding climate changes [Munchaev et al., 2012].

In the first centuries CE, temperature and humidity levels were comparable to modern conditions. However, between the 4th and 8th centuries CE, the climate in Europe became drier and warmer, leading to the shrinking of peatlands and falling lake levels. During the Medieval Warm Period (7th to 14th centuries CE), the climate in the Northern Hemisphere became notably milder and warmer, causing a sharp reduction in the ice cover of the northern seas. This period, also known as the Medieval Climatic Optimum, featured mild winters, expanded agricultural land, and a notable increase in both food production and population. Some American researchers suggest that the classical Mayan civilization collapsed during this time due to prolonged droughts [Medieval Climatic Optimum]. In the Caucasus, there was a significant retreat of glaciers in the Greater Caucasus, increased river flows from glacial melt, a drop in the Caspian Sea level, and the formation of deflation basins, all indicative of a warmer climate [Phys. geog. CR, 2006].

By the 14th century, a new phase of cooling had begun. Ice cover in the northern seas increased, and intra-seasonal climate variability also grew, marking the onset of the Little Ice Age. Some sources date the beginning of this period to the 14th century, while others place it in the 17th century, with its effects lasting until the mid-19th century. Key characteristics of the Little Ice Age include the expansion of mountain glaciers and a decline in arable and pasture land. This period is discussed in detail in B. Fagan's book published in 2021 [Fagan, 2021]. However, some researchers, such as A.S. Monin and colleagues, argue that the term "Little Ice Age" is inappropriate, as there was no continuous cooling over the entire period [Monin et al., 1979].

In the Caucasus, the Little Ice Age manifested through a rise in the Caspian Sea level, a weakening of continental climate patterns, increased precipitation, and other features [Phys. geog.

CR, 2006].

IV. Discussion

In the 16th century, the Alpine glaciers began to advance noticeably, but by around 1700, some retreat was observed. However, at the same time, glacier growth was recorded in Iceland and Norway, with a maximum in Sweden occurring around 1710. Significant glacier movements occurred again in the 1720s in the Alps, Scandinavia, the USA, and Alaska. In Alaska, glaciers had already started advancing into the valleys from the 14th century. After some stabilization in the late 16th century, Alaskan glaciers resumed their advance. In the 1740s-1750s, particularly strong glacier advances occurred in Northern Europe, Iceland, and Alaska. Glacier expansion in the Alps continued through the 1760s-1790s, reaching a maximum in 1820. A global peak in mountain glaciation in regions such as the Alps, Iceland, Norway, North America, and the Patagonian Andes was noted in 1850. The last significant global glacier movement occurred between 1850-1860, marking the end of the Little Ice Age.

The timing of climatic changes during the Little Climatic Optimum and the Little Ice Age varied between different regions of the Earth. The exact causes remain unclear, but some hypotheses suggest increased volcanic activity and a decrease in atmospheric CO_2 concentrations as potential factors behind the Little Ice Age.

After the Little Ice Age, a warming period began in the late 19th century, with particularly pronounced warming during the 1920s and 1930s. Climate fluctuations in the late 19th and 20th centuries were measured directly through meteorological observations. In many parts of the world, such as the Caucasus, Pamir, Tien Shan, Altai, and the Himalayas, glaciers retreated during this period, leading to a reduction in their overall area. For instance, the glacier area in the Caucasus shrank by 8.5% between 1890 and 1946 [Modern climate, Internet resource]. Other data, including long-term monitoring from the High-Mountain Geophysical Institute in Nalchik, indicate that glacier coverage in the Greater Caucasus decreased by 40% over the last century.

By the 1940s, this warming trend reversed, leading to a cooling period that peaked in the mid-1960s. Glacier expansion occurred in the early 1960s as a result. However, since the 1970s, a new phase of warming began, which persists today [Monin, 1979]. Since the 1990s, there has been an increase in precipitation, a rise in the Caspian Sea and groundwater levels, and a continued reduction in glacier areas.

There is substantial evidence that the warming following the Little Ice Age extended into the late 19th and early 20th centuries. Instrumental observations show that the average global temperature increased by 0.5°C during this period. Rising global temperatures impact the ocean, causing thermal expansion and, consequently, sea level rise. Changes in precipitation distribution over land have also been observed. Since the early 20th century, sea level measurements show a consistent rise, with an average increase of 4-5 cm per century. Therefore, the past 100 years have been characterized by a period of climate warming.

Since the 1970s, a new phase of global warming has prompted widespread attention to the future of Earth's climate. Various explanations for the causes and consequences of climate change have emerged. The first theory attributes climate change to human activities, particularly the industrial use of hydrocarbon fuels, which has intensified the greenhouse effect. The second theory suggests that global warming is driven by cosmogenic factors, unrelated to human activity. A third theory posits that climate change is a result of the synergy between both anthropogenic (greenhouse effect) and natural processes [Global climate change].

Academician V.M. Kotlyakov acknowledges the greenhouse effect's existence but highlights the difficulty in determining its exact contribution to global climate change. Carbon dioxide is the primary contributor to the greenhouse effect, and efforts to reduce its emissions include transitioning from traditional fossil fuels to renewable energy sources. The Kyoto Protocol (1997) and the Paris Agreement (2015) have been pivotal in setting international standards for reducing CO_2 emissions. In response, renewable energy has gained increasing attention, with the share of renewables in the global energy mix growing to 14% over the past 50 years [Degtyarev, 2022]. Looking forward, population growth and economic expansion will shape global energy demand, with projections indicating a decrease in the use of oil and coal and an increase in gas and renewable energy. According to the World Energy Council, renewable energy sources could surpass 40% of the global energy balance [Salygin, 2021].

Thus, climate change in the Holocene, as in earlier geological epochs, is largely a natural historical process. Following the glacial and interglacial periods of the Pleistocene, the Holocene has witnessed alternating periods of warming and cooling, punctuated by shorter episodic climate shifts. The current warming phase, which began in the 1970s, continues today. However, the industrial revolutions and the increasing consumption of fossil fuels have introduced a significant anthropogenic factor into this natural process.

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